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RESEARCH MEMORANDUM

TRACKING PERFORMANCE OF A SWEPT-WING FIGHTER WITH A DIRECTOR-TYPE RADAR FIRE-CONTROL SYSTEM AND SCOPE PRESENTATION

By Howard L. Turner, George A. Rathert, Jr., and Donovan R. Heinle

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RESEARCH MEMORANDUM

TRACKING PERFORMANCE OF A SWEPT-WING FIGHTER WITH A DIRECTOR-TYPE RADAR FIRE-CONTROL SYSTEM AND SCOPE PRESENTATION

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SUMMARY

Flight tests were conducted with an F-86D airplane equipped with a director-type radar fire-control system with scope presentation of the attack display. The effects of two attack-computer parameters and one attack-display parameter on the tracking performance in the manual mode of operation were investigated.

A marked deterioration in tracking performance, due to noise effects, brought about by the lack of radar target resolution at short ranges was noted for ranges less than 600 yards.

A deterioration in tracking performance was found as the steering-dot sensitivity varied during an attack as a function of the projectile time parameter. Tracking performance was adversely affected by a sensitive steering dot at short projectile times (2 sec) and by a sluggish steering dot at long projectile times (8 sec).

The static gain of the attack display, that is, the steering-dot scale factor, markedly affected the tracking performance through the attack display. An optimum value for this parameter is suggested.

The mean gun-line wander, in tail-chase tracking with the attack display, was approximately 1 mil greater than the corresponding mean gun-line wander obtained from fixed-sight tracking.

INTRODUCTION

For some time the Ames Laboratory has been engaged in investigating the effects on tracking accuracy of various types of fire-control systems

in different aircraft. An integrated study of the effects of the dynamics of the piloted airplane on the tracking accuracy with a fixed sight is summarized in reference 1. Individual studies of the effects of the dynamics of the airplane and of the airplane flight-control system on tracking accuracy of disturbed-reticle-type fire-control systems are given in references 2 to 4.

The criteria of merit of a given pilot-airplane fire-control system used in the references is simply the tracking accuracy of the complete system expressed by the root mean square tracking-line aim wander as a measure of the pilot's effectiveness, and of the corresponding rms gun-line wander as a measure of the weapon system effectiveness. Accumulated experience has shown, however, that the experienced research pilot is extremely adaptable and can track almost as effectively with a poor fire-control system or airplane flight-control system as he can with any optimum weapon system configuration. The tracking experiences on which these conclusions were based were accumulated under conditions when the pilot had visual contact with the target and hence was able to estimate the maneuvering potential of the target. A study in which the tracking pilot had visual target contact but in which the tracking airplane was flown by a manually operated director system is reported in reference 5.

The present investigation deals with the tracking characteristics of a director-type radar fire-control system in which the tracking pilot has no visual contact with the target, the steering information being presented to the pilot in an attack display on a radar scope. The effects on tracking accuracy of two attack-computer parameters and one attack-display parameter will be examined. All tracking data presented include the effects of radar noise.

ATTACK COMPUTER

In an interceptor fire-control system, the relative position and rates of change of position of the target with respect to the interceptor are measured by an airborne target detector such as radar. This radar-measured information is fed to an attack computer which computes the correct course the interceptor must fly to effect a kill and presents the proper steering information to the pilot, for manual control, or to the autopilot, for automatic control. Generally, either a lead-collision attack or a lead-pursuit attack is used, depending upon the particular armament available. In the lead-collision mode, the attack course is computed to direct the interceptor into firing position at only one instant; in the lead-pursuit mode the attack course is computed to direct the interceptor to be in firing position continuously. In both modes, the computer solves the same basic equations and the proper steering signals for the desired type of attack are computed and presented to the pilot on the radar scope.

The typical attack computer solves for the miss that would occur if the present course were maintained by the interceptor, computes the angle that the interceptor must turn through to reduce this miss to zero, and generates the steering signals to be presented to the pilot on the attack display.[1] For example, the azimuth miss, perpendicular to the line of sight, can be described by the equation,

$$M_H = R\omega_D T_p + F \sin \theta \tag{1}$$

the computed angle to turn through to reduce this miss to zero can be determined from the equation,

$$\delta_{AZ} = \frac{\cos \theta}{VT_p + F}\left(R\omega_D T_p + F \sin \theta\right) \tag{2}$$

and the steering signal presented to the pilot can be described as

$$\delta_s = K_s \delta_{AZ} \tag{3}$$

where

F distance traveled by the projectiles, relative to the interceptor, during the time interval T_p

K_s steering signal scale factor

M_H azimuth miss perpendicular to the line of sight from the target to the interceptor

R slant range from the interceptor to the target

T_p projectile time (projectile time of flight in the lead-pursuit mode or time from "now" until the projectile passes through the plane of the target in the lead-collision mode)

V interceptor velocity

δ_A azimuth steering signal

δ_{AZ} azimuth angle the interceptor must turn through to be on a zero miss course

[1]The development and detailed discussion of these miss and steering equations are available in reference 6.

δ_S steering signal presented to the pilot on the attack display

θ azimuth bearing of the target with respect to the interceptor armament datum line

ω_D horizontal angular velocity of the tracking line (radar beam) in space

Since the $\cos \theta/VT_p+F$ term in equation (2) is a multiplying factor affecting only the sensitivity of the steering signal, it is often replaced by a $1/T_p$ term to simplify the mechanization of the attack computer. Hence, equation (2) is replaced by

$$\delta_A = \frac{1}{T_p}\left(R\omega_D T_p + F \sin \theta\right) \tag{4}$$

The range parameter, R, and the time parameter, T_p, are time variant in both lead-pursuit and lead-collision maneuvers. It can be seen from the preceding equations that these parameters are the primary controllable variables governing the computation of the steering signal δ_A. As shown in equation (4) above, the range parameter, R, acts as a gain modifying the rate term in the steering equation; the projectile time parameter, T_p, modifies the rate term and also changes the gain or sensitivity of the steering signal through the $1/T_p$ term. The influence of these attack-computer parameters on the resulting tracking performance is difficult to determine if the parameters are permitted to vary during any given attack. Hence, the attack computer was modified to permit the study of these parameters on a fixed-time basis where R and T_p could be varied independently. For this investigation R was varied from 200 yards to approximately 1000 yards and T_p was varied from 8.0 seconds to 2.0 seconds. These values of R and T_p were considered typical of values of these parameters during the more critical phases of lead-collision and lead-pursuit attacks.

ATTACK DISPLAY

In a fire-control system for the modern all-weather interceptor, the proper steering information, computed in the attack computer, is presented to the pilot in an attack display on a radar scope. A simplified diagram of a typical attack display is shown in figure 1. Detailed descriptions of the information shown in this display are given in references 6 and 7.

Three basic factors govern the ability of a pilot to track effectively through the attack display:

(a) The method of presenting steering and orientation information

(b) The filtering of radar noise from steering information

(c) The static gain or scale factor of the steering errors

The method of presenting the steering and orientation information to the pilot and the effects of the filtering of radar noise are problems of such magnitude that they will be the subject of separate investigations.

The steering-dot scale factor, K_s, is a static gain defined as the amount of steering error required to move the steering dot 1 inch on the attack display. Wide tolerance in this parameter is often allowed between displays in a given fire-control system. In the E-4, E-5, E-6, and MG-2 fire-control systems, for example, the steering-dot scale factor is permitted to vary as much as ±50 percent between displays. The practice of assigning military pilots to different aircraft from mission to mission is widespread; hence, the pilots' tracking capabilities may be prejudiced if the steering-dot scale factor is permitted to vary over a wide range. The effects of changes in steering-dot scale factor, K_s, on the tracking performance are included in this investigation.

EQUIPMENT AND PROCEDURES

The director-type fire-control system available to this investigation was a modified E-4 fire-control system installed in an F-86D all-weather interceptor (fig. 2). Steering information was supplied to the pilot in an attack display on a 5-inch cathode-ray tube. The AN-APA 84 attack computer available for this investigation was modified to permit static examination of normally time-variant attack-computer parameters during lead-pursuit-type tracking runs that were long enough to produce statistically significant data. A simplified functional block diagram of the fire-control system is given in figure 3. The attack-computer parameters R and T_p and the steering-dot scale factor, K_s, are indicated on this diagram with an asterisk. Technical descriptions of the attack computer and the fire-control system are given in references 6 and 7.

The test maneuver, shown in figure 4, was the same standardized maneuver upon which the previous work reported in references 2 to 5 was based. The maneuver contains elements that are common to both the lead-collision beam attack and to lead-pursuit attacks as far as the maneuvering of the attacking aircraft is concerned. All flights were conducted at 30,000 feet at 0.70 Mach number with a target-interceptor speed ratio of 1:1. Interceptor maneuvers were limited to 1.5g to avoid the adverse effects of tracking near the buffet boundary. The F-84F and F-86A target aircraft used in this investigation were equipped with two rear-pointing corner reflectors mounted in external fuel tanks.

Photographic measurements of the gun-line wander were obtained by a 16mm GSAP camera photographing the target aircraft through an N-9 fixed sight mounted in the interceptor. Tracking-line wander data were obtained from a modified 16mm GSAP camera photographing the pilot's attack display. No rockets were fired during these tests. The ballistic computer was used to bias the steering dot to cause the interceptor to fly approximately 100 feet below the target to avoid the target wake and to prevent the vapor trails of the target from obscuring the photographic measurements of gun-line wander. Biasing the steering signals to cause the attacker to fly below the target did not materially affect the tracking performance.

TESTS, RESULTS, AND DISCUSSION

Fixed-Sight Tracking

The fixed-sight tracking characteristics shown in figure 5 were obtained to establish the tracking effectiveness of the basic pilot-airplane combination so that the tracking characteristics attributable to the fire-control system and scope presentation of steering information could be seen. The fixed-sight tracking characteristics with the F-86D airplane previously reported in reference 1 (shown in fig. 5 as a dotted line) could not be used for this purpose because of a major redesign of the flight-control system of the F-86D prior to this investigation. All tracking data reported herein were obtained with the improved flight-control system.

Tracking With Scope Presentation

The tests reported herein were conducted with the pilot tracking the target with the aid of an attack display on a radar scope. The attack display has been shown in figure 1. In these tests the pilot had no direct visual indication of the position or attitude of the target during the test maneuver. A supplementary instrument indicating the range to the target, in yards, was provided to assist the pilot in maintaining the desired test conditions.

As previously discussed, the azimuth steering signals generated in the attack computer can be expressed by equation (4). It has been shown that each of the parameters R and T_p acts as a gain affecting the steering signals generated in the attack computer and that the steering signals are further modified by the steering-dot scale factor, K_s, which is the static gain of the attack display. Each of these parameters was tested independently, the parameters affecting the other gains being set at values which preliminary studies had indicated were near optimum. The effects of the parameters R, T_p, and K_s on the tracking performance are

shown in figures 6, 7, and 8, respectively. The values of the fixed parameters are shown in the following table corresponding to the figure number in which the data are presented.

Figure	Primary variable	Fixed parameter				
		V, yd/sec	F, yd	T_p, sec	R, yd	K_s, yd/sec/in.
6	R	231	500	4	---	24
7	T_p	231	500	---	900	24
8	K_s	231	500	4	900	---

For convenience, the discussion of these results will be divided into three parts as follows:

(a) The effects of the range term, R, both as a gain on the angular rate signals and as a parameter affecting the radar resolution of the target shown on the attack display.

(b) The effects of projectile time, T_p, acting as a gain regulating the sensitivity of the steering dot.

(c) The effects of the static gain of the attack display, that is, the steering-dot scale factor, K_s.

Range.- In most lead-collision beam attacks and in the tail-chase portions of the lead-pursuit test maneuver, with a director-type fire-control system, high antenna rates are associated with short ranges and low antenna rates are associated with long ranges. Hence, it would be reasonable to expect that the over-all gain of the steering signal would not be materially affected by range changing the steering signal gain through the $(R\omega)$ term in the steering equation. However, the effects of variations in range on the gun-line wander in tail-chase maneuvers shown in figure 6 indicate that the gun-line wander deteriorates when range is reduced below approximately 600 yards. This deterioration in gun-line wander might be caused by the $F \sin \theta$ term in the steering equation since it can be shown that the indicated angular error, θ, varies inversely with range for a given target displacement error. However, in the tail-chase maneuver where the values of θ are small, the effects of the $F \sin \theta$ term on the tracking performance are considered negligible.

Under visual tracking conditions, a deterioration in tracking performance at short range is not usually encountered since the pilot shifts from tracking the whole target image at long range to tracking some point on the target at short range, thereby effectively changing the gain of the system. With a scope presentation of the attack display,

however, the pilot cannot adapt to point tracking at short range. This is due to the inability of radar to distinguish any particular point on the target. The lack of target resolution at short range shows up in the attack display as excessive radar noise. When the gain of the steering signal is adequate to indicate small errors at long range, large error indication and excessive noise leading to an overcontrol condition can be expected in short range tracking resulting in the increase in the measured gun-line wander shown in figure 6.

It is noted that the deterioration in tracking would not be expected to affect lead-collision attacks since the armament is usually fired by the time the range has closed to 500 yards. Lead-pursuit attacks, however, may be affected when firing is conducted at ranges as short as 200 yards.

Projectile time.- It has been shown that the projectile time parameter T_p varies the magnitude of the steering signal as given by equation (4) through the $1/T_p$ term statically and through the lead angle term, $R\omega_D T_p$, dynamically. Since T_p varies both the static and dynamic characteristics of the steering equation, it can be considered as a parameter governing the "sensitivity" of the steering dot. As T_p varies during during the course of an attack, it is of interest to examine the effects of variation in steering-dot sensitivity on the tracking performance as shown in figure 7. These data are summarized in the table below:

Projectile time, sec	Mean radial gun-line wander $\bar{\sigma}$, mils	Scatter containing 90 percent of data, mils
2	4.9	3.3 to 6.0
4	3.8	3.0 to 5.0
6	5.0	3.1 to 7.4
8	6.4	3.6 to 10.0
Projectile time, sec	Mean radial steering-dot wander $\bar{\sigma}$, in.	Scatter containing 90 percent of data, in. on scope face
2	0.073	0.041 to 0.105
4	.040	.032 to .051
6	.042	.033 to .056
8	.052	.034 to .094

The amount of scatter present, as indicated in the table above, and bounded by the shaded area in figure 7, shows the range of values which includes 90 percent of the observed data. For example, at $T_p = 4$ seconds the mean gun-line wander is 3.8 mils with 90 percent of the data falling between 3.0 and 5.0 mils. The scatter of the data is of particular significance since it is an indication of the difficulty that the pilot is

encountering in obtaining repeatable data at a given set of conditions. The data shown in the table above and in figure 7(a) show higher steering-dot wanders and corresponding gun-line wanders for both the low and high sensitivity settings. At $T_p = 2.0$ seconds, corresponding to a high steering-dot sensitivity, the pilot exhibited a tendency to overcontrol. This overcontrol increased the gun-line wander and also induced extraneous noise into the steering dot (due to the interaction between the radar antenna and own-ship motions reported in ref. 8) which caused the steering-dot wanders to increase. At the low sensitivities, corresponding to a T_p of 8.0 seconds, the steering dot appeared to be sluggish. This lack of sensitivity coupled with the heavy filtering, employed in the attack display to compensate for radar noise, created a tendency for the pilot to reduce steering errors through a series of control motions. The resultant increase in gun-line wander was brought about by the time required to reduce the error and by the increase in steering-dot wander induced by the pilot control motions. It would appear from these results that it would be more desirable, from the tracking standpoint, to maintain a fixed value of steering-dot sensitivity during the attack.

In figure 7 the mean gun-line wander obtained with fixed-sight tracking with the test airplane and flight-control system is shown for comparative purposes. It can be seen that at the steering-dot sensitivity corresponding to a projectile time of approximately 4 seconds, the minimum mean rms gun-line wander obtained with the attack-display tracking is approximately 1 mil higher than the mean rms gun-line wander obtained with fixed-sight tracking where the pilot had visual contact with the target. The small increase in gun-line wander shown for the attack-display tracking is not considered particularly significant. To determine completely the loss in tracking effectiveness due to scope display tracking, it would be necessary to obtain gun-line data in transient conditions. Equipment limitations inherent in the fire-control system prevented obtaining such information in this investigation.

Steering-dot wanders obtained during steady-turn portions of the test maneuver are shown in figure 7(b). These data exhibit the same trends as the tail-chase data shown in figure 7(a); however, the magnitude of the steering-dot wanders and the scatter in the data are considerably greater because of an interaction between own-ship motions and the radar antenna inherent in the antenna design as reported in reference 8. Since the rate gyros used to compute the lead angles are mounted on the radar antenna, this interaction in maneuvering flight resulted in erratic lead-angle computations. The pilots' attempts to keep the steering dot centered caused the aircraft to change lead angle continuously during the turn, thereby making it impossible to measure a gun-line wander in turning flight that would be comparable with a gun-line wander obtained when the lead angle was constant as in the steady-turn conditions shown in references 1, 3, 4, and 5.

Steering-dot scale factor.- The steering-dot scale factor, or the static gain modifying the steering signal presented on the attack display, has been defined earlier in the report as the amount of steering error required to move the steering dot 1 inch on the attack display. As shown in the preceding sections, the steering errors are computed in the form of a miss distance divided by a time parameter and, hence, have the dimensions of yards per second. The steering-dot scale factor K_s, therefore, has the dimensions of yards per second per inch.

The results of flight tests conducted to examine the effects of changes in steering-dot scale factors on the tracking performance are shown in figure 8. The data from these tests are summarized in the table below:

Scale factor K_s, yd/sec/in.	Mean radial gun-line wander $\bar{\sigma}$, mils	Scatter containing 90 percent of data, mils
11.5	4.4	3.0 to 7.4
24.0	4.0	3.9 to 5.0
37.0	5.1	4.3 to 6.3
Scale factor K_s, yd/sec/in.	Mean radial steering-dot wander $\bar{\sigma}$, in.	Scatter containing 90 percent of data, in. on scope face
11.5	0.071	0.056 to 0.086
24.0	.040	.032 to .051
37.0	.035	.028 to .040

As in figure 7, the shaded areas in figure 8 indicate the scatter boundaries containing 90 percent of the observed data.

As indicated in the table above and in figure 8 the mean steering-dot wander obtained with a steering-dot scale factor of 11.5 yd/sec/in. was relatively high, resulting in a correspondingly large amount of scatter in the gun-line wander data, although the mean gun-line wander was not excessive. The pilot indicated that this sensitive scale factor appeared to be near the upper limit of tolerability and, although reasonably satisfactory for tail-chase flight, it could be expected that this sensitive scale factor would lead to drastic overcontrol in maneuvering flight. This tendency toward overcontrol in maneuvering flight is evident in the steering-dot wander data shown in figure 8(b). The data in figure 8(b) are adversely influenced by the interaction between the steering signals and own-ship motions induced by the manner in which the pilot manipulated the flight controls.

With a steering-dot scale factor of 37.0 yd/sec/in. the steering dot appeared excessively sluggish. As shown in the table above and in figure 8(a) the mean steering-dot wander in the tail-chase portion of the maneuver was low (approximately 0.035 rms). The corresponding mean gun-line wander was somewhat higher than the wander obtained with the other scale factors. The sluggishness of the steering dot limits the pilots' ability to perceive small errors on the attack display and, hence, the gun-line wander is inadvertently allowed to build up. With a sluggish steering dot, poor tracking effectiveness could be expected in maneuvering flight.

On the basis of the tracking data shown in figure 8, a reasonable value for the steering-dot scale factor would be 25 yd/sec/in. with a tolerance of ±20 percent. A steering-dot scale factor tolerance of ±50 percent between attack displays in a given type fire-control system appeared to be excessive.

SUMMARY OF RESULTS

Flight tests were conducted with an F-86D airplane equipped with a director-type radar fire-control system with scope presentation of the attack display. The effects of two attack-computer parameters, range and projectile time, and one attack-display parameter, steering-dot scale factor, on the tracking performance in the manual mode of operation were investigated. The bulk of the data was obtained in tail-chase flight because the tracking performance in maneuvering flight was adversely affected by an inherent interaction between own-ship motions and the steering signals.

In the computation of the steering signals in the attack computer, range would not be expected to materially change the gain of the steering signal through the $(R\omega)$ term in the steering equation. However, the tracking performance data showed a marked increase in gun-line wander for ranges below 600 yards. This reduction in tracking performance is largely due to excessive noise brought about by the lack of target resolution on the attack display at short ranges.

The projectile time parameter acts as a gain regulating the sensitivity of the steering signal generated in the attack computer. During a typical attack the pilot experiences first a sluggish steering dot, which results in a large gun-line wander, and then a sensitive steering dot, which causes overcontrol. From a tracking performance standpoint, it would appear desirable to maintain the steering-dot sensitivity at a fixed value throughout the attack.

The steering-dot scale factor is the static gain of the steering signal presented on the attack display. A high gain causes the pilot to

overcontrol and a low gain prevents the pilot from detecting small errors. The test data indicate that a steering-dot scale factor of 25 yards per second per inch ±20 percent appears to represent an acceptable compromise between low gun-line wander and a steering dot sensitive to small errors.

During the course of this investigation a comparison was made between the mean gun-line wanders obtained while tracking through an attack display and while tracking with a fixed sight and visual target contact. The data showed that under tail-chase tracking conditions and with the attack-display and attack-computer parameters set at their optimum values, the mean root mean square gun-line wander with attack display tracking was approximately 1 mil higher than the mean root mean square gun-line wander obtained with fixed-sight tracking. This small increase in gun-line wander with attack-display tracking is not considered to be particularly significant.

Ames Aeronautical Laboratory
National Advisory Committee for Aeronautics
Moffett Field, Calif., Oct. 1, 1957

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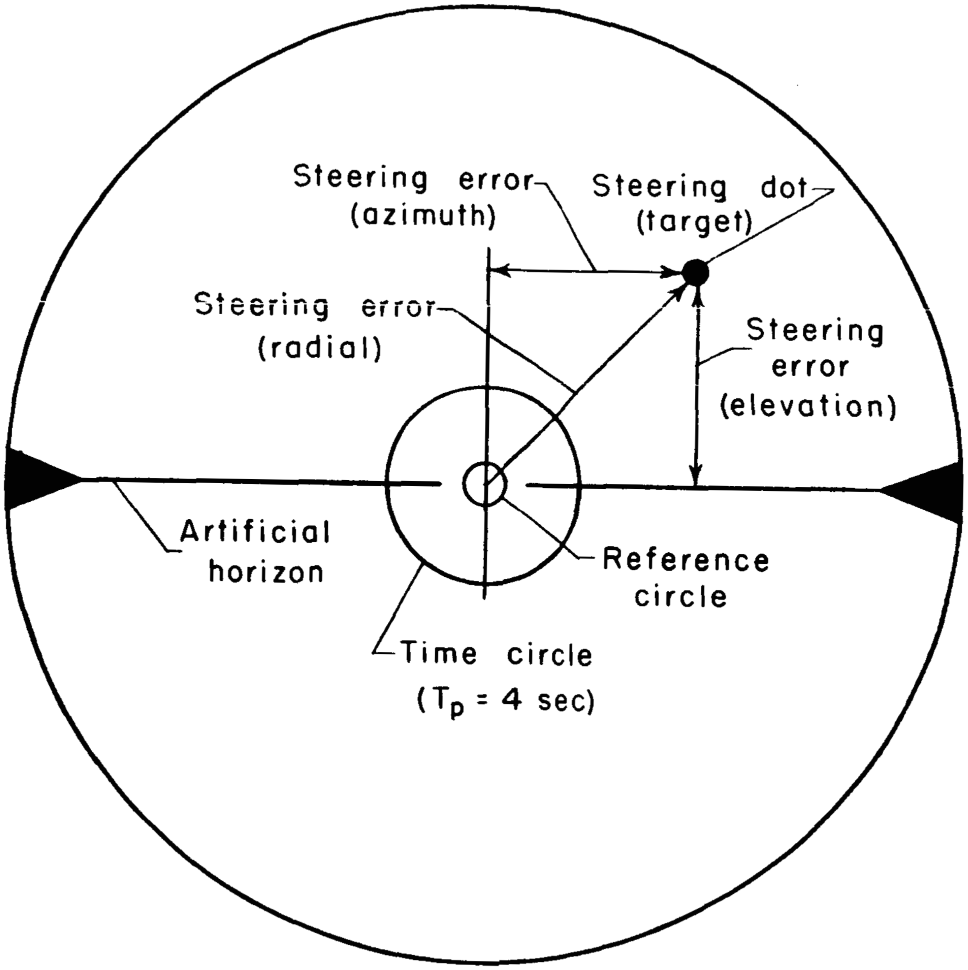

Figure 1.- Attack display.

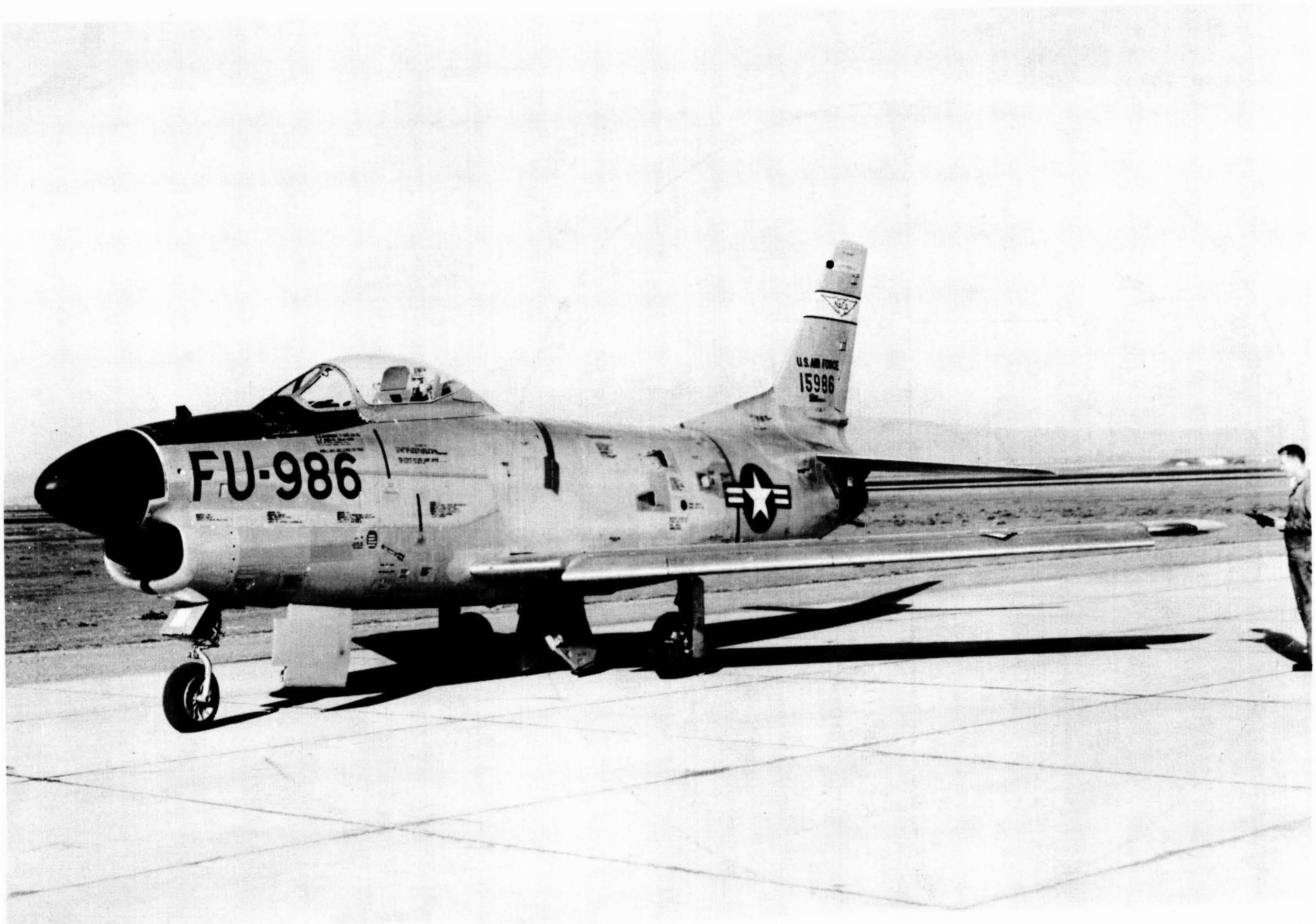

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Figure 2.- Test interceptor.

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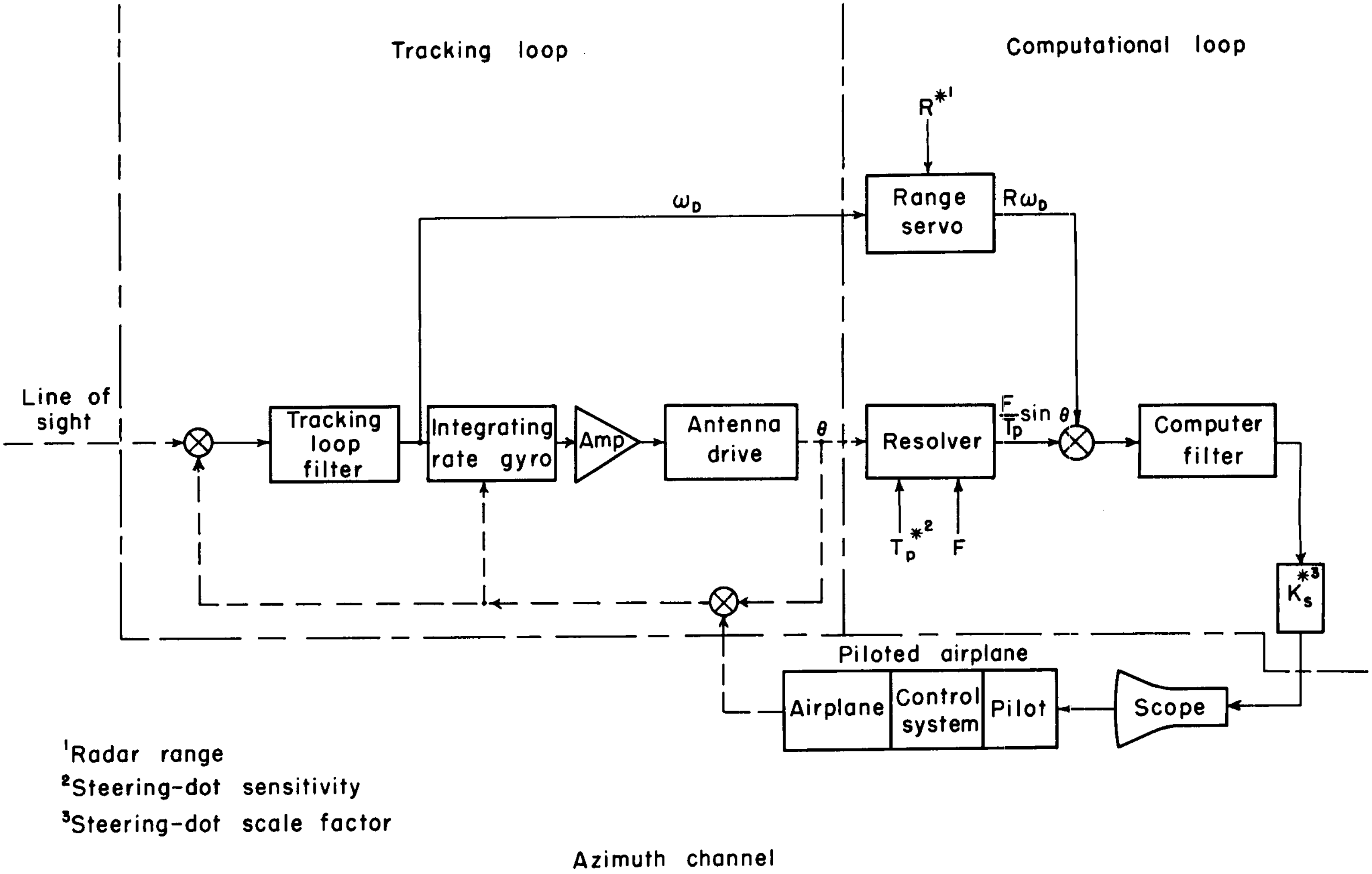

Figure 3.- Simplified functional block diagram of the director-type fire-control system.

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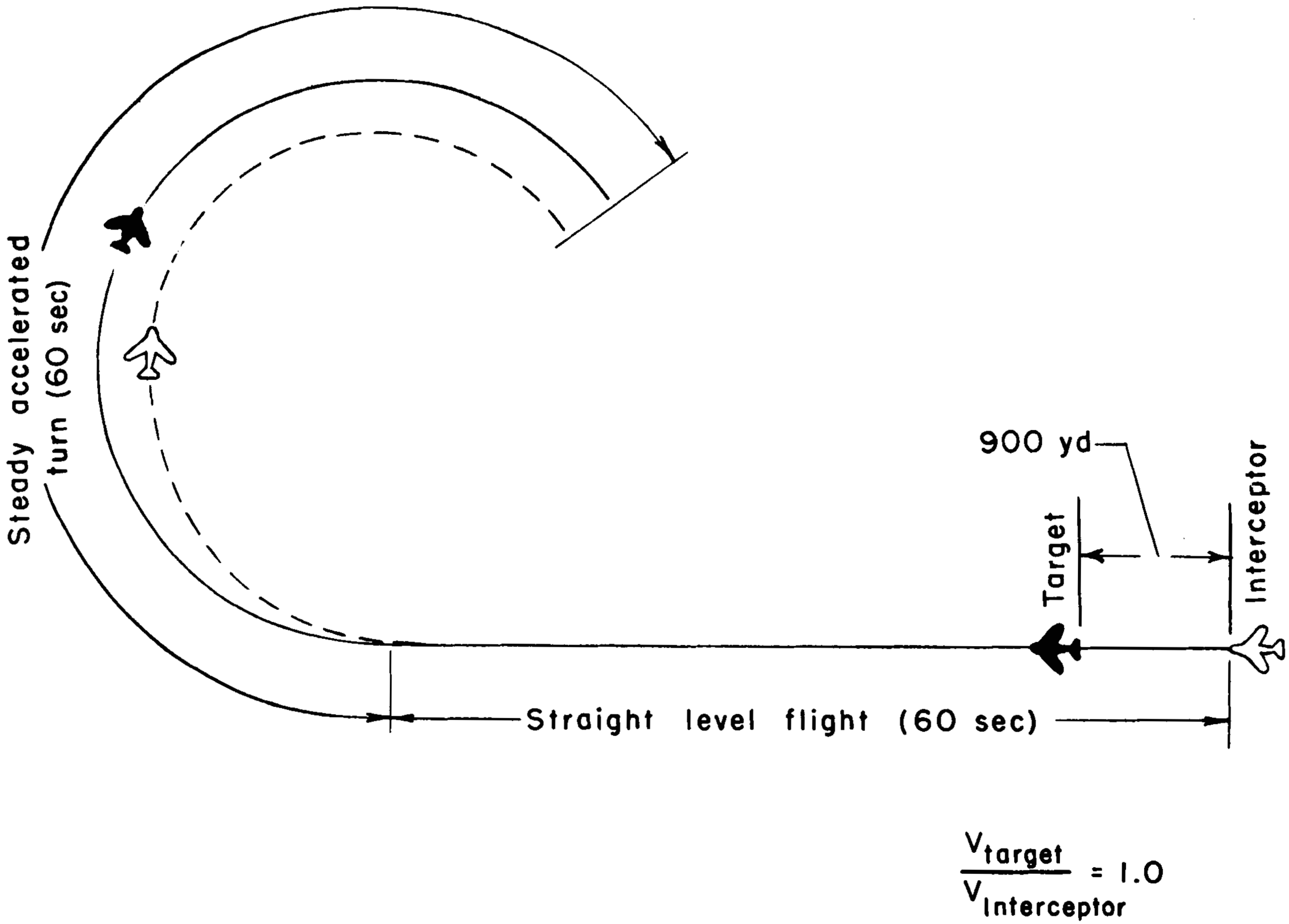

Figure 4.- Standard maneuver used in this investigation.

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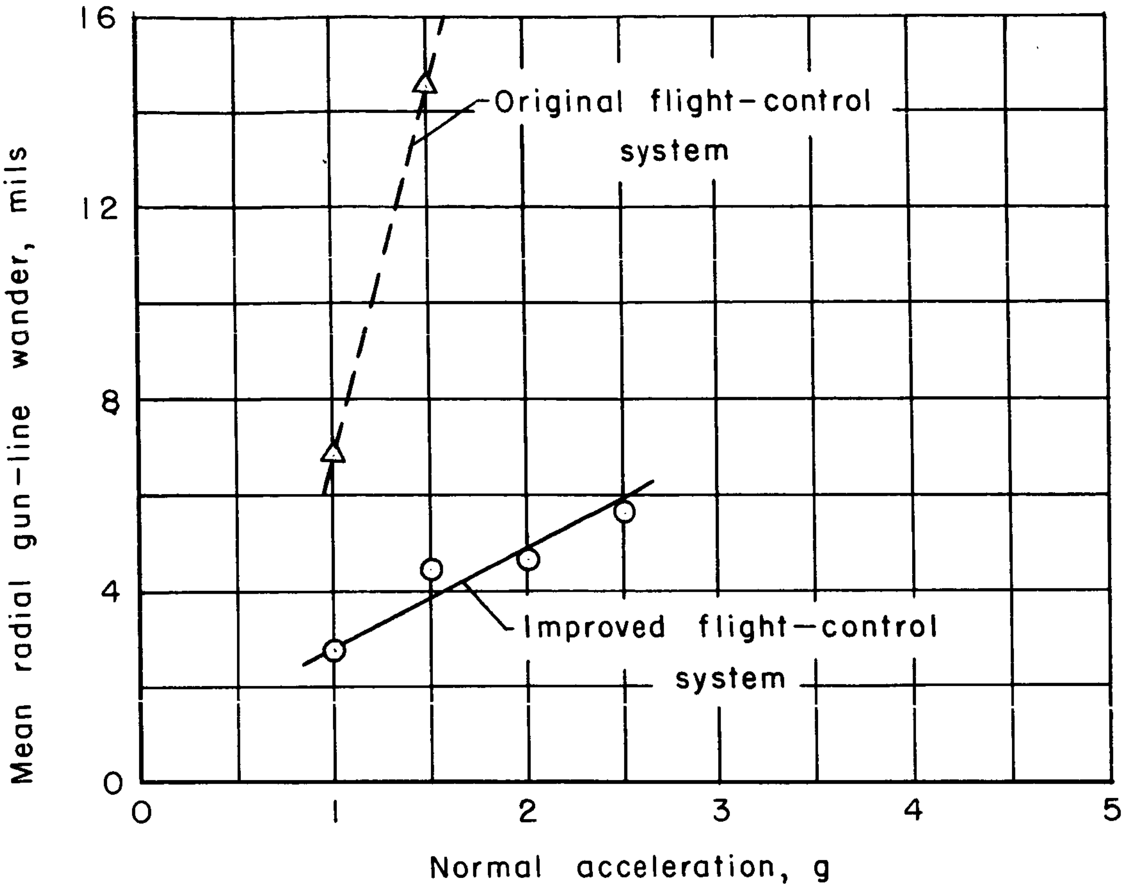


Figure 5.- Fixed-sight tracking characteristics; F-86D airplane, Mach number = 0.70, altitude = 30,000 feet.

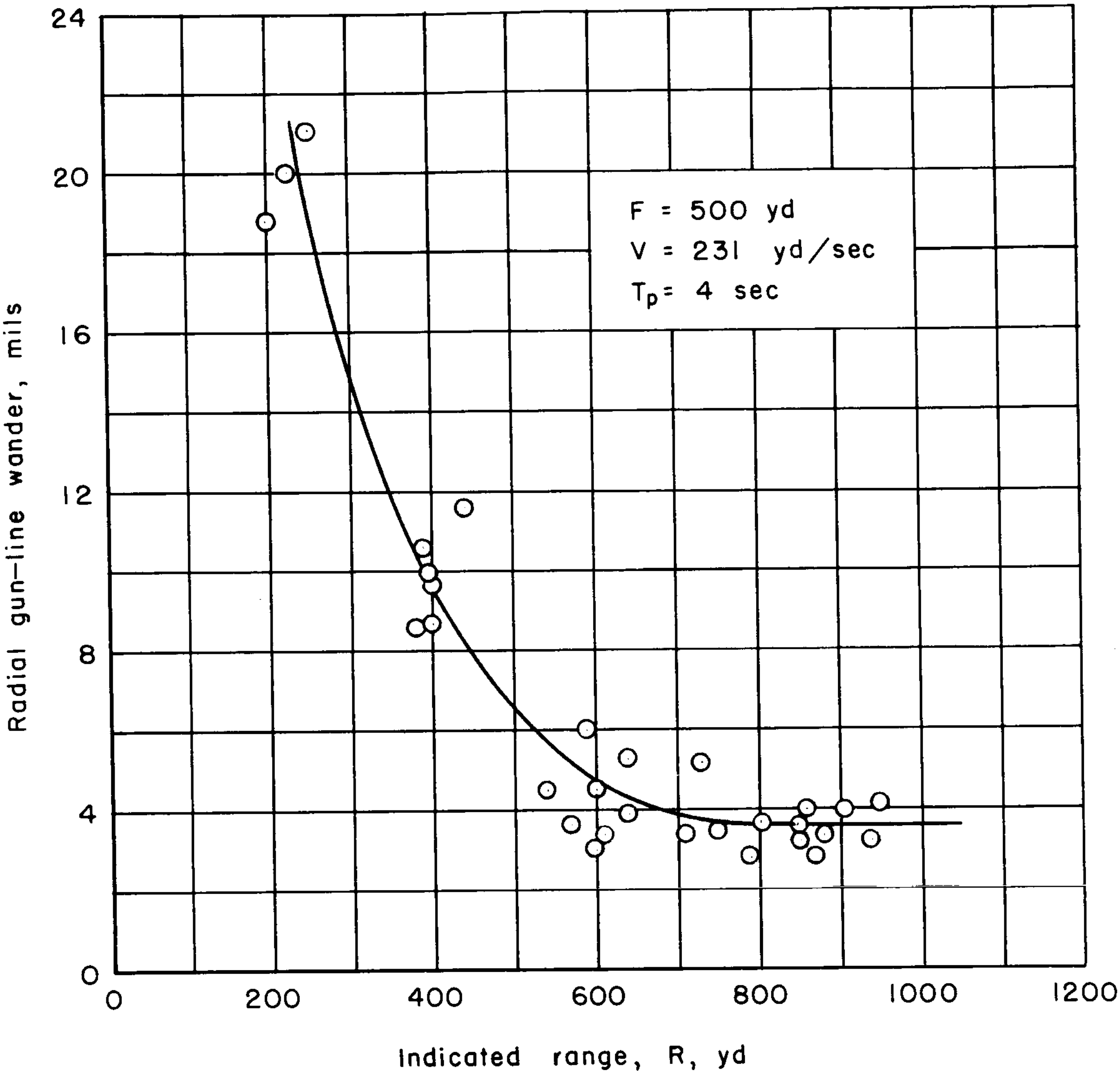
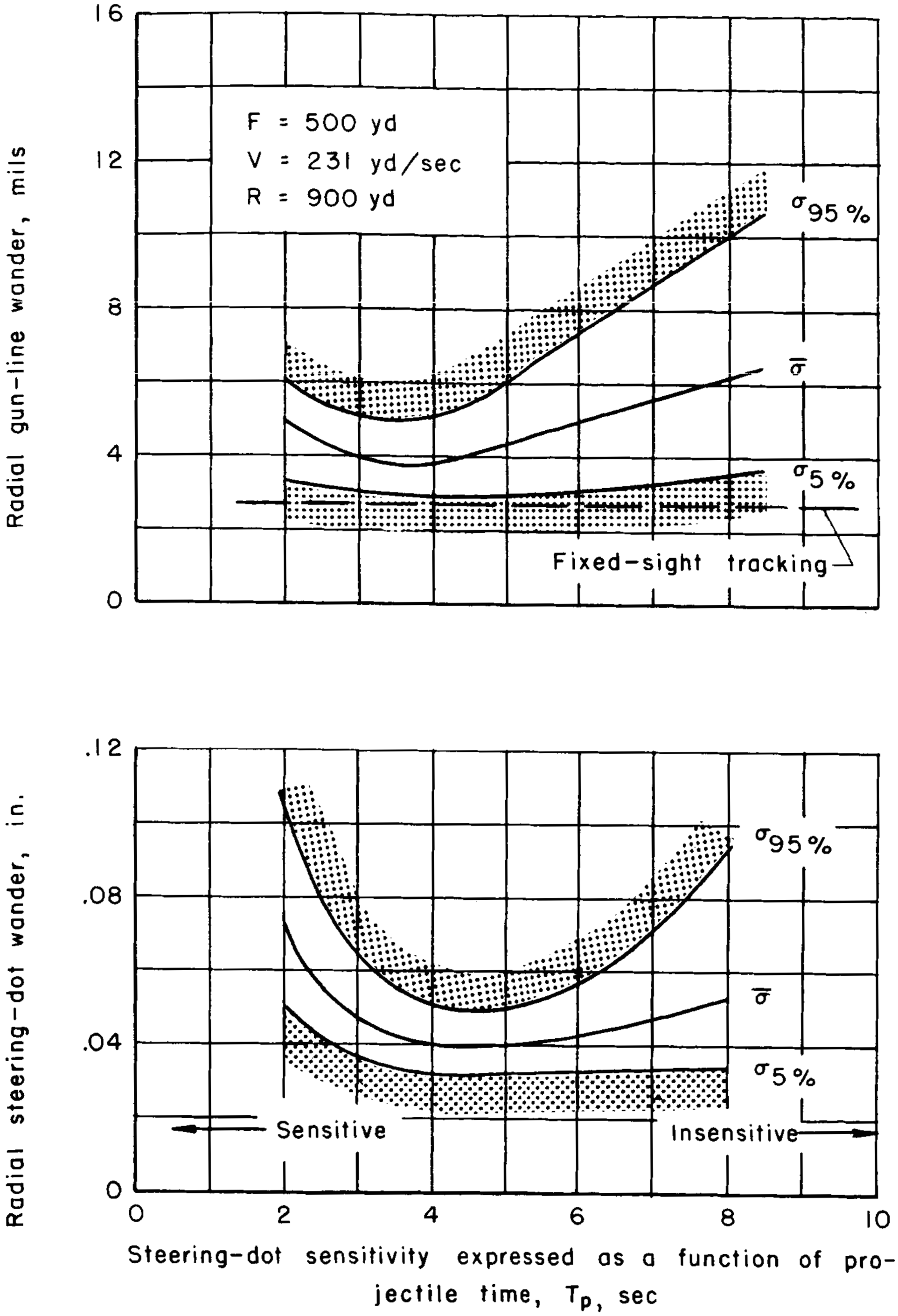
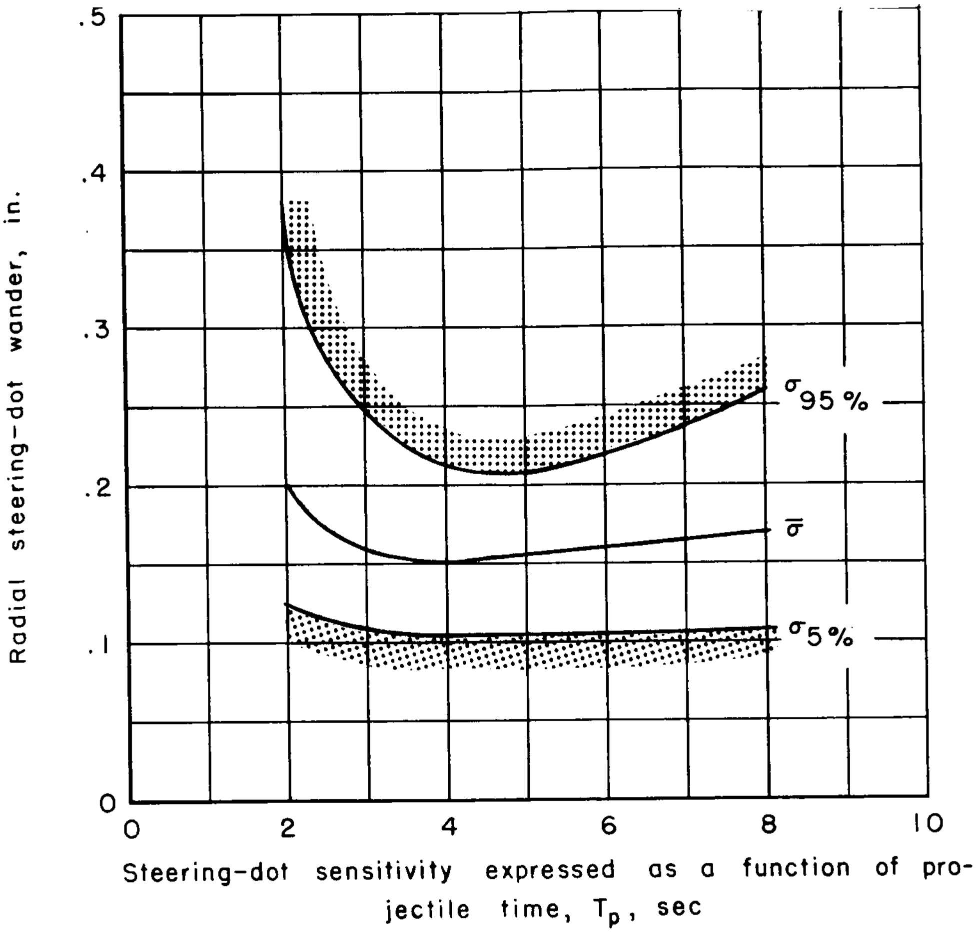


Figure 6.- Effect of range on the gun-line wander in a tail chase maneuver; K_s = 24 yd/sec/in.



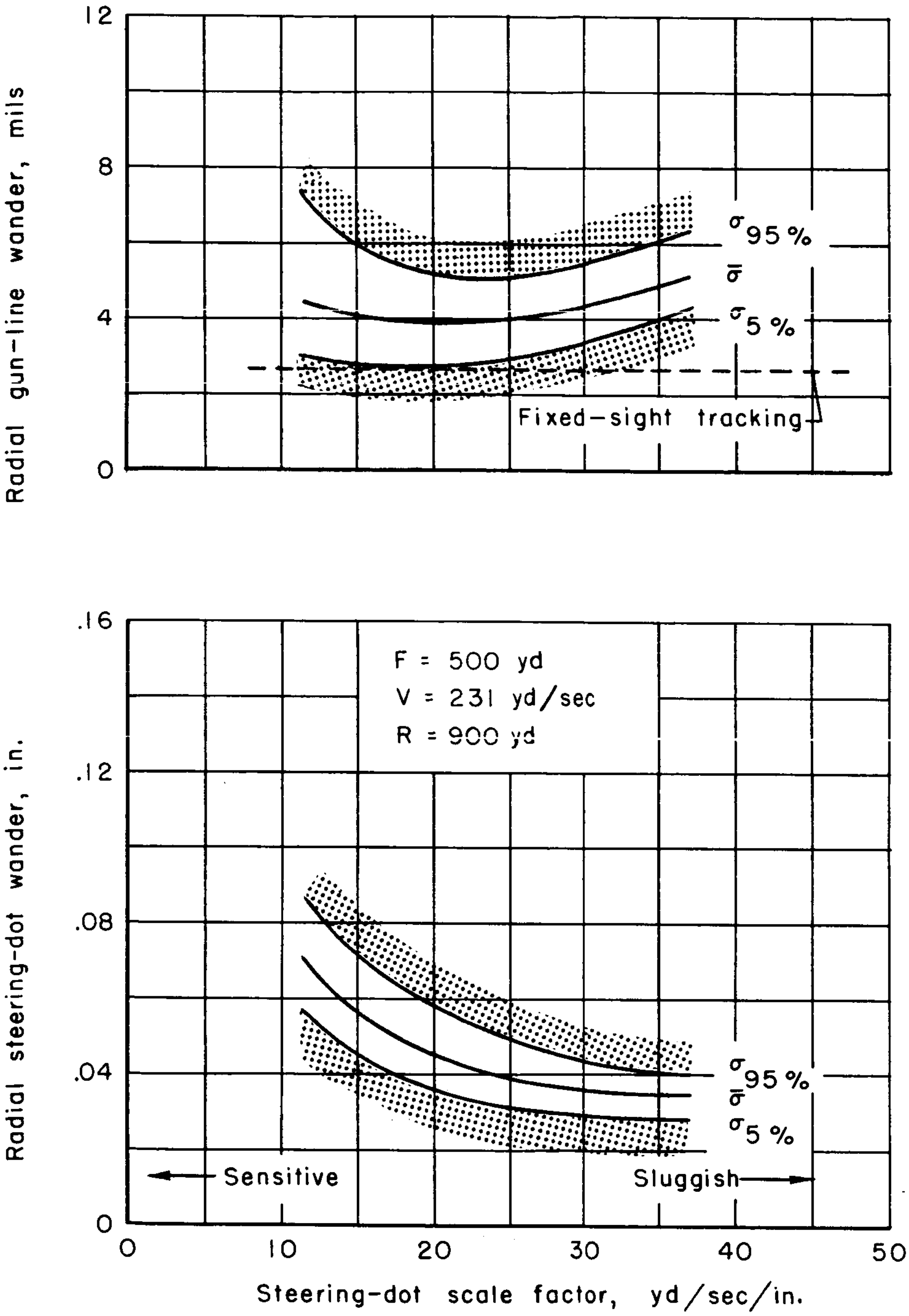
(a) Tail chase.

Figure 7.- Effect of steering-dot sensitivity on tracking performance; K_s = 24 yd/sec/in.



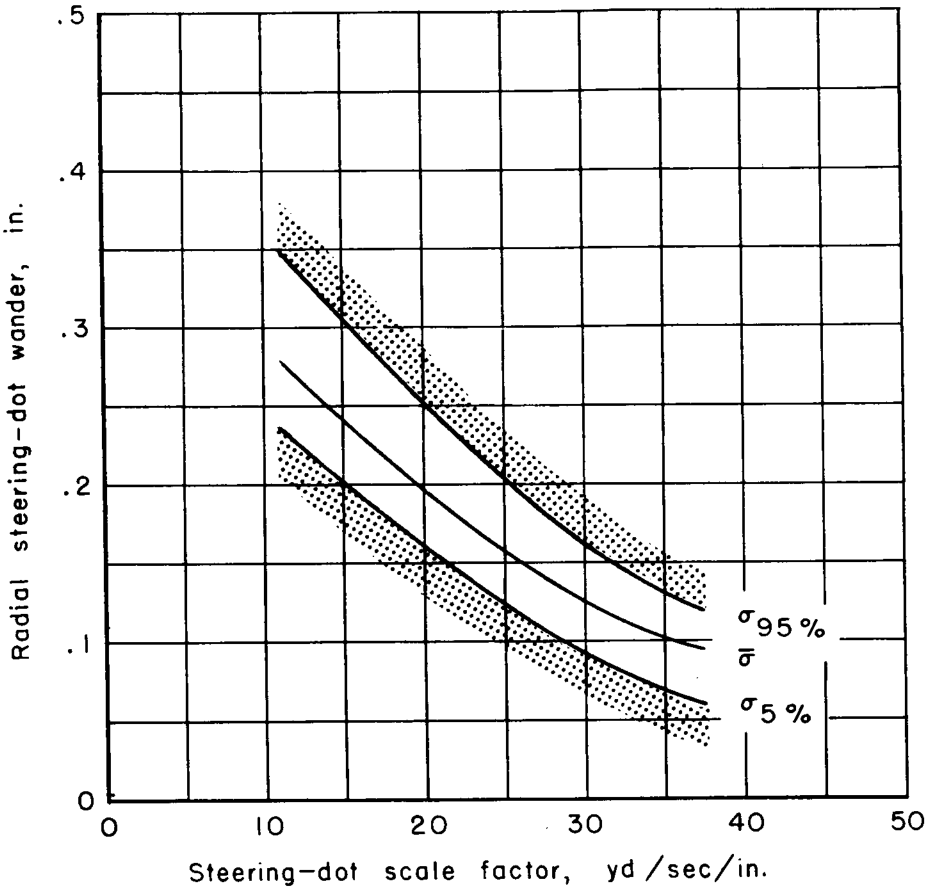
(b) Steady turns.

Figure 7.- Concluded.



(a) Tail chase.

Figure 8.- Effect of steering-dot scale factor on tracking performance; $T_p = 4$ sec.



(b) Steady turns.

Figure 8.- Concluded.

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